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Article

Hybrid Chemical Enhanced Oil Recovery Techniques: A Simulation Study

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Abstract: Simultaneous utilization of surfactant and preformed particle gel (henceforth; PPG) flooding on the oil recovery enhancement has been widely investigated as a preferable enhanced oil recovery technique after the polymer flooding. In this paper, a numerical model is developed to simulate the profound impact of hybrid chemical enhanced oil recovery methods (PPG/polymer/surfactant) in sandstone reservoirs. Moreover, the gel particle conformance control is considered in the developed model after polymer flooding performances on the oil recovery enhancement. To validate the developed model, two sets of experimental field data from Daqing oil field (PPG conformance control after polymer flooding) and Shengli oil field (PPG-surfactant flooding after polymer flooding) are used to check the reliability of the model. Combination of preformed gel particles, polymers and surfactants due to the deformation, swelling, and physicochemical properties of gel particles can mobilize the trapped oil through the porous media to enhance oil recovery factor by blocking the high permeable channels. As a result, PPG conformance control plays an essential role in oil recovery enhancement. Furthermore, experimental data of PPG/polymer/surfactant flooding in the Shengli field and its comparison with the proposed model indicated that the model and experimental field data are in a good agreement. Consequently, the coupled model of surfactant and PPG flooding after polymer flooding performances has led to more recovery factor rather than the basic chemical recovery techniques.

Keywords: chemical flooding; preformed particle gel (ppg); conformance control; polymer flooding; oil recovery factor

1. Introduction

To provide sustainable oil demand in numerous industries, it is important to increase the recoverable oil from the oil reserves. Drilling the new exploration wells or enhanced oil recovery methods considered as the preferable ways to produce more oil volume [1–7]. Chemical recovery techniques revolutionize the way petroleum industries operate the full range of reservoir management and how to optimize each method to eliminate unnecessary expenditures virtually [8–14]. The three primary mechanisms of chemical flooding are; capillary number rise is caused to mobilize the residual oil, reduce the ratio of mobility to improve the sweep efficiency, and oil emulsification that leads to facilitate the production rate. Polymer flooding is considered as one of the efficient chemical enhanced oil recovery techniques especially in heavy oil reservoirs to improve sweep efficiency, however, it has specific limitations in actual oil fields operational performances. As a result, one of the chief aims of enhanced oil recovery (henceforth; EOR) techniques is to improve the sweep efficiency of the reservoirs after the polymer flooding processes, which is known as the conformance control [15–23].

The usual materials employed as the conformance agent are bright water, preformed particle gel (henceforth; PPG), and polymer microgels. PPG is considered as one kind of efficient polymeric

gel to increase the rate of sweep efficiency regarding the overcoming the drawbacks of in-situ gels. To improve the sweep efficiency of the reservoir after polymer flooding, the following steps are done sequentially [24–27]. First of all, PPG slug is injected into the high permeable zones. Next, the surfactant is injected to displace the remained oil to increase displacement efficiency. Within the interaction of surfactant and PPG, some of the characteristics of both phases have been changed, such as the dynamic feature of PPG [28–34].

Gel particles due to their deformation, swelling, and physicochemical properties can mobilize through the porous media and its pore throats even in long distances to block the high permeable channels that are occupied by water. Feng et al. (2009) proposed a filtration model to describe the interaction between the remaining polymers and PPG in the desorption and deposition processes. They simulated the blocking pathways in the presence of gel particles, and the proposed model has a good agreement with the experimental field data to enhance oil recovery [35]. In the injection of gel particles in the reservoir, three principal mechanisms have occurred as the following mechanisms; swelling the gel particles after their contact with water phase which leads to increase the equivalent volume, deposition of gel particles in the narrow pore throats might be plugged when the pressure gradient of macro-pores is lower than particles pressure gradient in the breakthrough time. Moreover, the reaction between remained polymers and gel particles has caused to form the floc units and subsequently leads to an increase in the equivalent volume. Due to the previous experimental evaluations which are based on the PPG transport mechanisms in the porous media, it is experienced that the propagation property of PPG is fundamentally differentiated from the controlling of deep bed filtration by the surface deposition. According to the Wu and Bai investigation, a numerical model has been developed to illustrate the propagation of a gelled particle by the utilization of non-Darcy flow in the porous media [36–40].

Gong et al. (2017) proposed a novel and developed chemical enhanced oil recovery methods which is known as branched preformed particle gel to enhance the oil production rate in hydrocarbon reservoirs. They performed some set of experiments for the sequential injection of branched preformed particle gel and polymer (hydrolyzed polyacrylamide) flooding to compare the oil recovery factor with single injectivity of each chemical agents. They concluded that sequential injection of branched preformed particle gel and hydrolyzed polyacrylamide would provide higher oil recovery factor as the combination of these chemical agents can provide an adjustable fluid mobilization in different permeable zones due to its deforming and blocking agents. Moreover, hydrolyzed polyacrylamide can increase the branched preformed particle gel sustained effect, which can help to increase the resistance factor [41].

He et al. (2018) investigated hybrid chemical enhanced recovery techniques on oil recovery enhancement. They combined branched-preformed particle gel, polymer and surfactant flooding, which has caused to reduce water-oil interfacial tension and control the mobility ratio after polymer flooding. Moreover, they optimize the combination of injectivity performances by performing a different set of experiments to ensure the proposed method would be economically variable for different reservoir characteristics. They concluded that there is any significant difference between the simultaneous or alteration injection of chemical agents on the pressure drop and oil recovery factor. However, simultaneous chemical agent injection would provide higher displacement and sweep efficiency [42].

Xu et al. (2019) proposed a novel experimental combination method to enhance oil recovery factor. They performed some set of experiments for the sequential injection of branched preformed particle gel and microbial polysaccharide (xanthan gum or diutan gum) flooding to compare the oil recovery factor with single injectivity of each chemical agents. The combined chemical agent has provided the pseudo-plastic fluid properties and good performance on the rheological characteristics of the reservoirs. They concluded that the addition of microbial polysaccharide to the branched preformed particle gel could improve the oil recovery factor rather than usual recovery techniques. Moreover, the proposed chemical method has more stability in high-temperature reservoirs and would an efficient technique

when aquifers have contained high salinity components [43]. Zhu et al. (2019) proposed a mathematical model based on the Buckley–Leverett equation to predict the Relative permeability curves in the case of branched-preformed particle gel flooding during oil recovery enhancement. They consider particle mesh and size distribution in their model and how it affects the relative permeability curves. Moreover, they found that particle size and particle mesh increment would enhance displacement efficiency, especially in low permeable zones [44,45].

We aimed to develop a numerical model simulate the profound impact of hybrid chemical enhanced oil recovery methods (PPG/polymer/surfactant) in sandstone reservoirs. Moreover, the restarting and deposition is taken into consideration by the utilization of a threshold pressure gradient. However, the results of this study indicated the good agreement between the numerical model and experimental evaluations; it would require validating the model by more actual field data to adjust the practical field parameters.

2. Methodology

2.1. Experimental Investigation

Regarding the promising conformance control of gel particles and its significant influence on the recovery performances especially after polymer flooding, Feng et al. (2013) developed an extended model by the consideration of gel conformance control parameter as a three dimensional model after the polymer flooding in Daqing oil field in China. A five-spot well was selected for the prediction of conformance control effect of preformed particle gel after polymer flooding. The geological properties of the studied field are statistically depicted in Table 1. Preformed particle gel flooding pattern was performed by a small size slug and a big small size slug of 65% and 35%, respectively. Moreover, they investigated the considerable influence of shear breaking, swelling, deformation migration, and remaining polymer synergy in the model. They concluded that the developed model would be a reliable tool to optimize the crucial parameters that are affected the gel particle performances through porous media (Feng et al. 2013).

Table 1. Geological properties of the Daqing oil field (Feng et al. 2013).

Layers	Sand Thickness (m)	Water Saturation (%)	Permeability ($10^{-3} \mu\text{m}^2$)
1	2.72	47.31	541.47
2	1.13	45.37	546.28
3	1.30	48.14	581.67
4	0.72	48.55	602.54
5	1.12	49.63	658.32
6	1.90	49.89	664.22

To validate the sequential injection of preformed particle gel and surfactant after polymer flooding, the Shengli oilfield pilot (sandstone water-wet) was chosen with the area of 0.275 km^2 (Sun, 2014). Reservoir characteristics of this oilfield are statistically depicted in Table 2.

Firstly, at the beginning of the injection of surfactant/PPG, the total recovery factor is relatively 54.5%. The injectivity scenario was contained the 0.05 PV of 1500 mg/L of polymer and 1500 mg/L of PPG and 0.03 PV of (1200 mg/L of polymer, 1200 mg/L of PPG, and 0.4 wt % of surfactant). In respect of the way, the three injectivity slugs of surfactant/polymer/PPG are being injected simultaneously.

Table 2. Reservoir characteristics of the Shengli oilfield (Sun, 2014).

Layer	Areal Permeability ($10^{-3} \mu\text{m}^2$)	Vertical Permeability ($10^{-3} \mu\text{m}^2$)	Porosity	Oil Saturation (%)
1	200	20	0.15	0.8
2	400	40	0.16	0.8
3	600	60	0.17	0.8
4	800	80	0.18	0.8
5	1000	100	0.19	0.8
6	1200	120	0.20	0.8
7	1400	140	0.21	0.8
8	1600	160	0.22	0.8
9	1800	180	0.23	0.8
10	2000	200	0.24	0.8

2.2. Interaction Between PPG and Surfactant

To calculate the polymer and PPG interaction, many types of research have been done regarding the adsorption of anionic polymers by the cationic PPG, which is caused by the electronic coupling effect. Therefore, the PPG apparent volume has been increased (Feng et al. 2013).

$$\phi'_{ppg} = \phi_{ppg} - SWR_{ppg} \quad (1)$$

This phenomenon is known as the synergy effect and the size of PPG by the swelling parameter. Equation (2) is used to consider the profound impact of surfactants and PPG on the gradient pressure (Cui et al. 2011; Wu and Bai, 2008). As can be seen in Equation (2), the higher value of surfactant concentration than critical micelles concentration (CMC), the micelles would be adsorbed by the PPG on the surface and subsequently has led to the less gradient threshold pressure rather than its original value ($\Delta p_{\text{gradient}(ppg)0}$). Moreover, d_1, d_2, d_3 are empirical correlations which is statistically described in next section.

$$\Delta p_{\text{gradient}(ppg)} = \begin{cases} \Delta p_{\text{gradient}(ppg)0} e^{-d_1 C_{\text{surf}} + d_2} & C_{\text{surf}} > \text{CMC} \\ \Delta p_{\text{gradient}(ppg)0}^{(1-d_3 C_{\text{surf}})} & C_{\text{surf}} < \text{CMC} \end{cases} \quad (2)$$

2.3. Governing Equations for Polymer and Surfactant Flooding

One of the chief aims of polymer flooding performances, when it is added to the water, is to increase the water viscosity and subsequently to improve the sweep efficiency regarding the lower viscous fingering. As the polymer's particle migration has no impact on the hydrocarbon flow, standard black oil equations could be used to solve the flow mechanisms. Therefore, the polymer is operated as a dissolved phase in water (it is known as the concentration of polymer in the water) the flow rate after polymer flooding is calculated as Equation (3) according to the principles of material balance equation (Gao et al. 1993).

$$Q = \frac{\partial(\phi S_w C_p)}{\partial t} + \frac{\partial[F_p \rho_R (1 - \phi) \hat{C}_p]}{\partial t} \quad (3)$$

where C_p is the polymer concentration, ppm; \hat{C}_p is the polymer adsorption concentration, ppm; F_p is the inaccessible pore volume, dimensionless; ϕ is the porosity, fraction; S_w is the water saturation, dimensionless; ρ_R is the rock density, kg/m^3 . In addition, the focus of this paper is to derive a numerical model for the preformed gel particle in the polymer by the simple modification of polymer flooding model. The principle phenomenon in the surfactant flooding is to decrease the saturation of residual oil and subsequently increase the displacement efficiency. As same as the polymer model, to derive a numerical model for surfactants, it is assumed that surfactant is a soluble component in the aqueous phase. Thereby, the flow rate after surfactant flooding is calculated as Equation (4) (Afsharpoor et al. 2010):

$$Q = \frac{\partial(\phi S_w C_{\text{surf}})}{\partial t} + \frac{\partial[F_{\text{surf}} \rho_R (1 - \phi) \hat{C}_{\text{surf}}]}{\partial t} \quad (4)$$

where C_p is the surfactant concentration, ppm; \hat{C}_p is the surfactant adsorption concentration, ppm; F_p is the inaccessible pore volume. Some of the physical properties of the surfactant, such as capillary pressure, relative permeability, and adsorption, are being illustrated in this model.

2.4. Governing Equations for PPG

PPG retention in the porous media has caused to the porosity reduction, and subsequently, the changes of porosity are calculated as Equation (5) (Civan, 2015);

$$\varnothing = \varnothing_0 - \varphi'_{ppg} \quad (5)$$

where φ'_{ppg} is the PPG retention in the porous media, fraction; \varnothing_0 is the original porosity, fraction. Due to the dependency of permeability to the porosity, the relation between both parameters are calculated as the following Equation (6) (Feng et al. 2013; Feng et al. 2009):

$$\left(\frac{K}{K_0}\right) = \left(\frac{\varnothing}{\varnothing_0}\right)^3 \quad (6)$$

The kinematic equations for the particles of the gelling agent are explained as the following equations for the deposition process Equation (7) and deformation-desorption processes Equation (8) (Liu and Civan, 1996);

$$\lambda = \lambda_0 \left(1 + \frac{\alpha\delta}{m}\right)^y \left(1 - \frac{\delta}{m}\right)^z \left(1 - \frac{\delta}{\delta_{max}}\right)^x \quad (7)$$

where λ is the filtration coefficient, 1/m; λ_0 is the initial filtration coefficient, 1/m; y , z , and x are the experimental indices, dimensionless; m is the geometrical constant parameter which is related to the grain sizes of the filler in the clean medium, dimensionless; α is the experimental coefficient; dimensionless, δ is the porosity reduction, and δ_{max} is the value of specific deposit saturation, dimensionless.

Desorption of gelled particles in the porous media has occurred regarding the gelled deformation in the higher-pressure gradients rather than the pressure gradient of breakthrough time. Feng et al. (2009) derived an analytical equation to define the kinematic performances of gelled particles desorption and deformation at any points as Equation (7).

$$\frac{\partial\delta}{\partial t} = -\psi\delta v \frac{\partial p}{\partial r} \quad (8)$$

where ψ is desorption coefficient, dimensionless; v is filtration rate, m/min.

Moreover, the continuity equation of the gelled particles is calculated as Equation (9):

$$-\frac{1}{r} \frac{\partial(rvC)}{\partial r} + q = \frac{\partial\delta}{\partial t} + \frac{\partial(\varnothing C)}{\partial t} \quad (9)$$

where C is the gelled particles mass concentration which is in the suspension mode, %; δ is the specific deposit, dimensionless; r is the distance from the injection well, m; v is filtration rate, m/min.

Therefore, for different boundary conditions, the Equations (7)–(9) are summarized as Equation (10):

$$\left\{ \begin{array}{ll} \lambda = \lambda_0 \left(1 + \frac{\alpha\delta}{m}\right)^y \left(1 - \frac{\delta}{m}\right)^z \left(1 - \frac{\delta}{\delta_{max}}\right)^x & P_G \leq P_{Gmax} \\ \frac{\partial\delta}{\partial t} = -\psi\delta v \frac{\partial p}{\partial r} - \frac{1}{r} \frac{\partial(rvC)}{\partial r} + q = \frac{\partial\delta}{\partial t} + \frac{\partial(\varnothing C)}{\partial t} & P_G > P_{Gmax} \end{array} \right. \quad (10)$$

where P_{Gmax} is the gelled particles pressure gradient at the breakthrough time (Feng et al. 2009).

However, according to the previous investigations about the considerable influence of different types of oil on the interfacial tension parameter, Mehrabian s. et al. (2017) proposed that different oils have different interfacial tension and subsequently, due to the similar relationship between capillary pressure and interfacial tension, higher interfacial tension has higher capillary pressure. In this study,

the proposed model was done for one type of oil in the studied oilfield and to investigate the considerable influence of this parameter it should require to provide more experimental investigations which would be done for further works by the utilization of this results and compare them (Mehrabian et al. 2018).

The following underlying assumptions were considered in this model to provide the impact of some field parameters that would affect the results of the model. Uniform suspension of PPG in aqueous phase has not significant enough and could be neglected. In comparison with the total swelling process, short swelling time of PPG is not considered as the influential parameters in the modelling performances. Moreover, due to more than 95% volume of composition is related to the water phase, density is close to field data and would not be a comparative parameter. Another parameter would have a slight impact on the permeability is the surface deposition, which should be considered in the proposed model (Wang et al. 2012). PPG physicochemical mechanisms such as deformation migration, shearing breaking, and water viscosity increment are contained in the proposed model.

3. Results and Discussion

3.1. Water Cut

The proposed model was verified by the utilization of real experimental data from the Daqing oilfield to provide the accuracy of the model for further prediction of field performance (Feng et al. 2013). To have a conformance control of PPG agent after polymer flooding, the investigated pilot from the Daqing oilfield. The percentage of water cut in the production well is appropriately estimated by the proposed model in the actual application of the studied field. It is schematically depicted in Figure 1. Therefore, PPG has played a substantial role in the sweep efficiency improvement of the studied oilfield after polymer flooding.

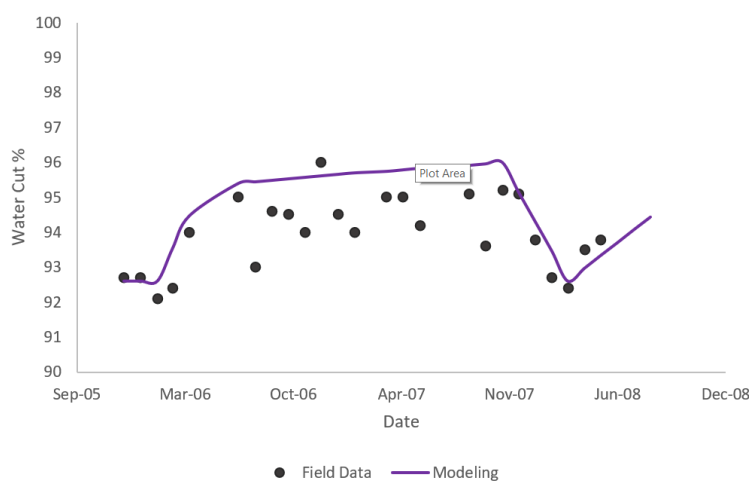


Figure 1. Water cut versus date in the production well for the actual field application.

3.2. Oil Rate

To validate the verification of surfactant/PPG model after polymer flooding with the actual field data, the pilot area was taken from the Shengli oilfield (Sun, 2014). The comparison of oil ratio in the proposed model and actual field performances are being shown in Figure 2.

Numerical analysis and mathematical modelling should be proposed in more detail by the consideration of field simulations to provide more reliability of the model. Thereby, the method of iterative coupling which was used by Tran et al. (2005) indicated that the results of the proposed model which was used in this paper are appropriate and effective in addressing the coupling of solid and fluid issues. Due to the complexity of PPG-polymer-surfactant encounter in the reservoirs, the feasible and stable numerical analysis should be taken into consideration to match the results of the proposed model with the realistic field data (Tran et al. 2005). Taksaudom P. (2014) proposed that regarding

the heterogeneity mitigation in sandstone reservoirs has caused by the effect of conformance control of PPG. Thereby, it indicated that the proposed PPG model could be administered in enhanced oil recovery techniques, especially for sandstone reservoirs. Furthermore, due to the complexity of flow performances in fractured reservoirs, chemical flooding modelling and simulation performances have needed further research and experimental evaluations (Taksaudom, 2014).

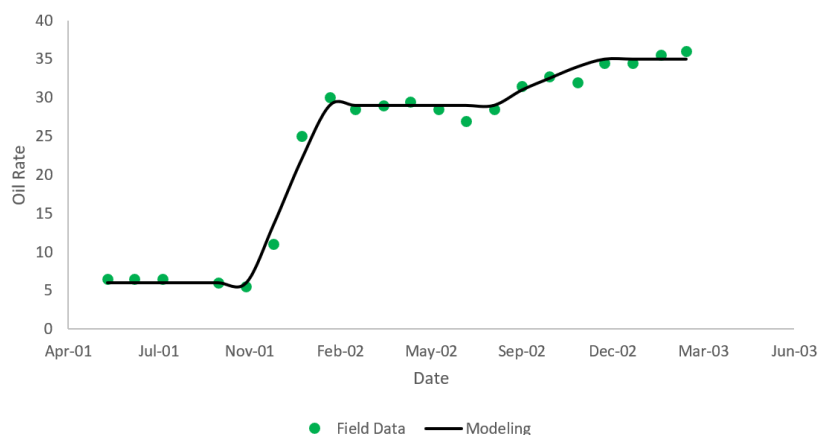


Figure 2. Oil rate versus date in the production well for the practical field application.

3.3. Injected Pressure

The governing equations, which contained complex nonlinear equations in this model, are being solved by the finite difference method because of its efficiently timesaving especially in the hybrid models of EOR processes. To calculate the surfactant and polymer concentration, saturation, and pressure, IMPSAT (implicit pressure and saturations and explicit component mole fractions) is used explicitly. Moreover, the fourth-order Runge–Kutta method and operator splitting technique are administered to lessen the numerical dispersions. To validate the results of the proposed mathematical model accurately and provide a good agreement with the implementation of the system in the realistic field circumstances, the experimental evaluations are being applied. To do this, the coupled model of surfactant/PPG is validated by the core flooding experiments. Firstly, to investigate the surfactant/PPG interaction, a 2D model is built by the Eclipse software with the matrix layer of 20*2*1 grid blocks without the impact of the polymer. Sequential injection of surfactant and PPG is implemented between two water injectivity scenarios which are more explicitly detailed in Muhammed FA et al. (2014). The coefficients which are used in this modelling to provide a proper matching with the experimental evaluations are $d_1 = 1.099 \times 10^{-3}$; $d_2 = 0.1825$; $d_3 = 0.0006$. The surfactant and PPG interaction is schematically depicted in Figure 3, which clearly shows that the proposed model has a good agreement with the injection of PPG and surfactant (Muhammed et al. 2014). The properties of the pilot field for PPG and surfactant is statistically depicted in Table 3.

Table 3. Properties of the pilot field for PPG and surfactant.

Depth (m)	1173–1230
Net Thickness (m)	14.2
Porosity (%)	33
Permeability ($10^{-3} \mu\text{m}^2$)	1.5–2.5
Oil Viscosity (mPa.s)	16.3
Temperature ($^{\circ}\text{C}$)	65.9
Salinity (mg/L)	5923

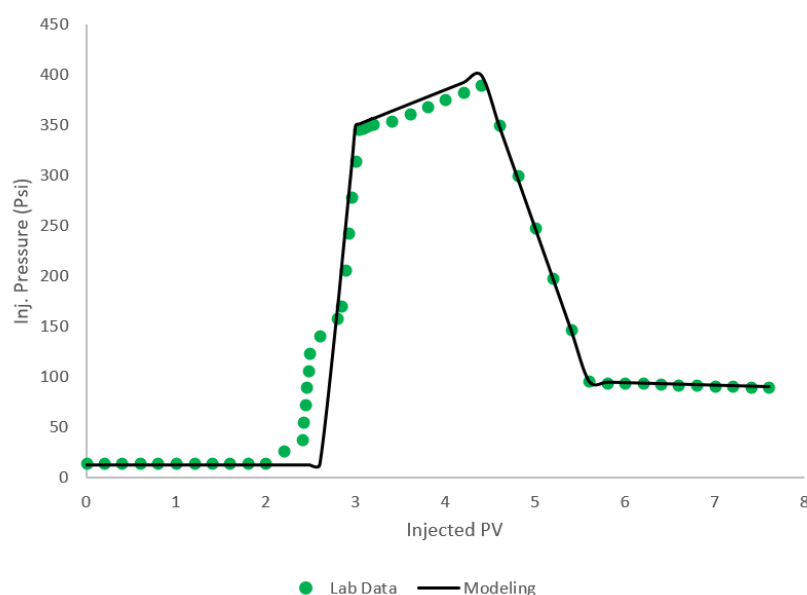


Figure 3. Calculating injected pressure versus injected PV in the surfactant/particle gel (PPG) interaction.

3.4. Recovery Factor

Firstly, a 2D model, which is simulated by Eclipse software, is used to investigate the surfactant, polymer and PPG interaction. Parameters of the physical model statistically described in Table 2 and the procedure of flooding operations are consistent slugs in Table 4.

Table 4. The procedure of flooding operations in the interaction of polymer/surfactant/PPG (Sun, 2014).

Stage	Procedure
1	Water injected into the core sample to reach the water cut up to 98%.
2	0.7 PV of polymer with the concentration of 1000 mg/L is injected.
3	0.3 PV of water is injected again.
4	0.3 PV of PPG with the concentration of 2000 mg/L is injected.
5	0.2 PV of cross-linking agent with a concentration of 100 mg/L is injected.
6	0.3 PV of surfactant is injected.
7	Water injected into the core sample to reach the water cut up to 98%.

Sequential injection of polymer/surfactant/PPG has led to blocking the large pore throats with the PPG particles, and the cross-linking agent had penetrated to the small throats. In the same regard as the previous experimental evaluation, the parameters for the interaction of surfactant/polymer and PPG are justified with the recovery factor history matching. Recovery factor versus injected pore volume for different injectivity stages is schematically depicted in Figure 4, which shows an appropriate agreement between the modelling and experimental analysis. Therefore, the proposed model accurately simulates the hybrid process of surfactant/polymer and PPG flooding.

The proposed model has some limitations, which should be taken into consideration before implementing the model. One of the crucial parameters, which highly influenced the chemical agent properties, is temperature, as it did not consider in any model. In high temperatures reservoirs, the efficiency of chemical agents has reduced as their stability is reduced in the presence of high temperature. Zhu et al. (2019) investigated the profound impact of microbial polysaccharide agent in the combination of chemical flooding as an experimental method. They found that this chemical agent would be stable in high-temperature reservoirs; however, it should be considered in the future analytical and numerical models to validate the models (Zhu et al. 2019). Moreover, it should be

noted that in complex reservoirs and unconventional reservoirs, it needed more corporate models and numerical analysis to be validated.

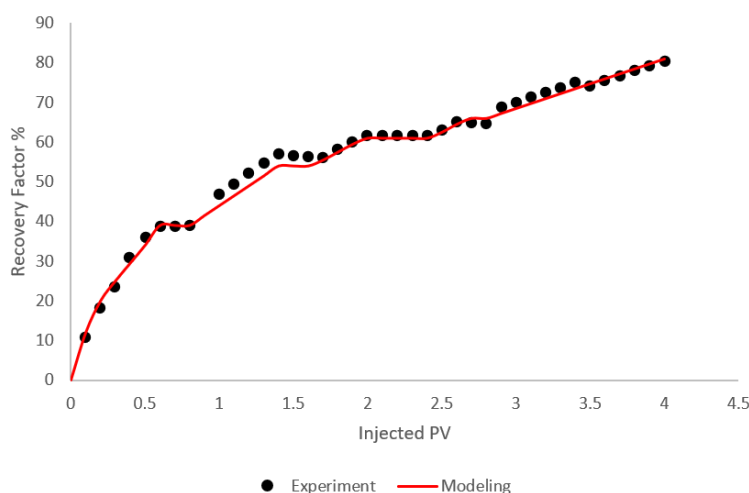


Figure 4. Recovery factor versus injected PV in the surfactant/polymer/PPG interaction.

4. Conclusions

PPG has played a substantial role in the oil sweep efficiency after polymer flooding performances and in this study; a numerical model is developed to simulate PPG conformance control after polymer flooding. It is based on the principle mechanism of surfactant and PPG in sandstone reservoirs and showed the effect of conformance control that significantly impacted by the heterogeneity of the sandstone reservoir. The threshold pressure gradient for the deposition of surfactant and PPG interaction is taken into consideration. According to the results of this study, there is a good agreement between the numerical model and experimental field data. Consequently, PPG conformance control influence would mitigate the heterogeneity of sandstone reservoirs, and the oil recovery factor has been increased dramatically regarding the increase of PPG concentration and injection volume. PPG-surfactant flooding after polymer flooding for the Shengli field (three-layer heterogeneous core flooding) was performed sequentially and as it is compared with the proposed model which indicated that the model and experimental field data has accurately matched together.

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Abbreviations

Parameter	Description
C_p	Polymer concentration, ppm
\hat{C}_p	Polymer adsorption concentration, ppm
F_p	Inaccessible pore volume, dimensionless
\varnothing	Porosity, fraction
S_w	Water saturation, dimensionless
ρ_R	Rock density, kg/m^3
ϕ'_{ppg}	PPG retention in the porous media, fraction

\varnothing_0	Original porosity, fraction
λ	Filtration coefficient, 1/m
λ_0	Initial filtration coefficient, 1/m
y	Experimental indices, dimensionless
z	Experimental indices, dimensionless
x	Experimental indices, dimensionless
m	Geometrical constant parameter which is related to the grain sizes of the filler in the clean medium, dimensionless
α	Experimental coefficient; dimensionless
SWR	the swelling ratio in the polymer solution
δ	Porosity reduction, dimensionless
δ_{max}	Value of specific deposit saturation, dimensionless
ψ	Desorption coefficient, dimensionless
v	Filtration rate, m/min
C	Gelled particles mass concentration which is in the suspension mode, percent

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